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Variability of Photovoltaic System Efficiency for Effective Solar Power Production over Akure, Southwest Nigeria

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ABSTRACT
In light of the global need for renewable energy as part of effort to reduce fossil fuel dependence, coupled with abundance of solar energy available over a tropical location, the need to effectively utilize photovoltaic energy cannot be overstated. Atmospheric weather parameters were measured on a daily basis from January 2007 to December 2011 at 30-minute intervals using the Davis 6162 Wireless Vantage Pro2 weather station. This work employs in-situ measurement of solar radiation over Akure (7°15'N, 5°06'E) for estimating the variability of solar PV system efficiency and effective energy budget in the region. The dependence of the system efficiency on weather variables and mounting options for installation was investigated. The energy balance, detailing the comparative advantage of the different mounting options were also carried out. Tracking option yield the most effective result and it offers appreciable energy balance that offsets any deficit associated with its high cost of installation.

KEYWORDS: Photovoltaic energy, Inverter, Direct current, Alternating current, Solar radiation

I. INTRODUCTION

Solar energy is a leading option for developing a cost-effective and practical global power source capable of replacing fossil fuels across all climatic regions. The amount of solar radiation that reaches the Earth's surface each year exceeds the planet's annual energy needs by more than 10,000 times. While large-scale solar thermal power plants are ideal for harnessing solar energy in arid and hot desert regions to generate electricity centrally, photovoltaic (PV) solar power is generally favoured for decentralized energy supply, delivering electricity directly at the point of consumption [1].Renewable energy resources exist in various forms across nearly all regions of the world [2].

Several studies such as[3], revealed that over 1.2 billion people lack access to electricity globally, and by 2040, approximately about 500 million individuals will still be without power primarily in rural areas.The increasing demand for electricity has led many countries to shift their focus toward more energy-efficient and renewable power sources. Nigeria, despite being a major producer of crude oil and natural gas, remains heavily reliant on these fossil fuels, which has negatively impacted its energy sector.Given the rapid depletion of fossil fuel reserves, insufficient refining capacity to meet domestic demand, and security challenges in oil-producing regions, the need for energy diversification cannot be overstated [4]. Nigeria is identified as one of the nations in the world with abundant renewable energy resources, including solar, wind, biomass, and small hydropower (SHP) [5].

Electricity demand is largely met through diesel and petrol generators, which serve as both primary and backup power sources for industries, institutions, shopping malls, commercial offices, households, and remote communities. However, reliance on fossil fuels must be reduced, as it not only increases the country's import burden but also exacerbates greenhouse gas emissions [6].Nigeria, located in the tropical region, has an abundance of solar energy resources that, if efficiently harnessed, could greatly reduce its reliance on fossil fuels. However, the intermittent nature of solar energy, which is influenced by environmental factors and available primarily on clear days, poses a challenge to the consistent reliability of solar power systems.The challenges facing solar energy production transcends night unavailability alone. Its efficiency is also a function of variable weather

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factors like solar intensity, cloud cover, humidity, and heat build-up among others. Also, the type of mounting options adopted for the PV system installation makes significant contribution to its efficiency variability. But if all these parameters are effectively characterized, coupled with a reliable energy storage mechanism, solar PV system has the potential of mitigating the energy problems of this Nation, especially as dependable backup power option. Consequently, this study will examine the variability of photovoltaic system efficiency for effective solar energy production over Akure, south-western Nigeria, and the structure for solar energy system are described in details below:

THE PHOTOVOLTAIC SYSTEM

The Sun has the potential to address future energy demands, as nearly all renewable energy sources stem from it either directly or indirectly [4]. Solar energy systems are broadly classified into two main types: photovoltaic (PV) systems, whereradiant light from sun is converted into electricity, and solar thermal systems, wherethe solar energy is transformed into heat [7], [8]. But, the major concern of this work is on photovoltaic (PV) system, a device that converts the solar energy from the sun into electrical energy [2], [7], [9].

PV-MODULE

A standard photovoltaic (PV) system comprises PV modules arranged in series to achieve higher voltage and in parallel to increase current for capturing sunlight. It also includes an inverter that converts direct current (DC) into alternating current (AC) and a battery bank for energy storage. The power output of PV modules varies, typically ranging from 20 to 60 Wp for smaller units to about 300 to 350 Wp for larger ones, depending on the module size and technology used.Low-power modules are generally utilized in stand-alone applications with minimal energy requirements. Conventional crystalline silicon modules, consisting of approximately 60 to 72 solar cells, have a nominal power rating between 120 and 300 Wp, based on their size and efficiency. PV modules can be customized according to installation site conditions and are designed to be durable, reliable, and resistant to harsh weather. Manufacturers typically guarantee that the module will retain at least 80% of its rated power output over a lifespan of 25 to 30 years [10].

INVERTERS

Inverters are vital for transforming the direct current (DC) generated by PV modules into alternating current (AC), enabling compatibility with the electrical grid and common household devices. They are necessary for smooth integration into the power distribution system. Inverters come in a range of different power capacities, from a few hundred watts (W) to several kilowatts (kW) [10].

BATTERIES AND CHARGE CONTROLLERS

Stand-alone PV systems rely on batteries such as Sodium-Sulfur (NaS) batteries, Nickel-Cadmium batteries, Flow batteries, lead-acid batteries to store energy for later use, with lead-acid batteries being the most common choice. Recently, newer high-performance batteries, such as lithium-ion batteries, have been developed specifically for solar applications, offering a lifespan of up to 15 years.Although, the actual lifespan of a battery, however, depends on how it is managed. Batteries are connected to the PV array through a charge controller, which safeguards the battery from overcharging and deep discharge. Additionally, the charge controlleralso provides system status information or support metering and payment for the electricity consumed [10].

There are three main types of solar panel mounting systems, including the fixed, adjustable, and tracking mounting techniques. The fixed mounting system remains stationary and is the simplest and most cost-effective option. The adjustable mounting system allows for changing the angle of the panels throughout the year to align with the sun’s varying position in different seasons. While more expensive than the fixed option, this system enhances the efficiency of the solar panels by significantly boosting their power output. The tracking system moves the panels to follow the sun's path from east to west during the day, as well as its seasonal changes in declination. It is the most efficient and most expensive of the three methods [11]. From the foregoing the variability of photovoltaic system efficiency is not only dependent on varying solar irradiation intensity and prevailing weather conditions, it also depends on type of mounting for the system. Consequently, this works evaluates the variability of PV efficiency of the different types of solar mount with respect to four prevailing factors - sun intensity, relative humidity, cloud cover and heat build-up.

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II. METHODOLOGY

SITE AND SCOPE OF DATA

Akure, located in southwestern Nigeria, serves as the capital of Ondo State. It lies between latitudes 7°15'N and 7°28'N, and longitudes 5°06'E and 5°21'E of the Greenwich Meridian, covering an area of about 41.2 km² [12]. The city's climate is significantly shaped by the southwestern monsoon winds from the Atlantic Ocean, which bring rainfall, and the dry, dust-laden winds from the Sahara Desert to the northwest. Consequently, Akure experiences a warm, humid tropical climate with a rainy season from April to October and a dry season from November to March [13-15]. Temperatures in Akure typically range from 22°C to 32°C, and the area is characterized by rainforest vegetation [16], [17]. Solar radiation data was collected through on-site measurements of weather parameters using the Davis 6162 Wireless Vantage Pro2 weather station, which is equipped with an Integrated Sensor Suite (ISS) [18]. The ISS includes sensors for the relevant meteorological parameters, and the sensor interface module (SIM) contains electronic chips that store and wirelessly transmit the recorded weather data to the console. The location of the study area is depicted in Figure 1.

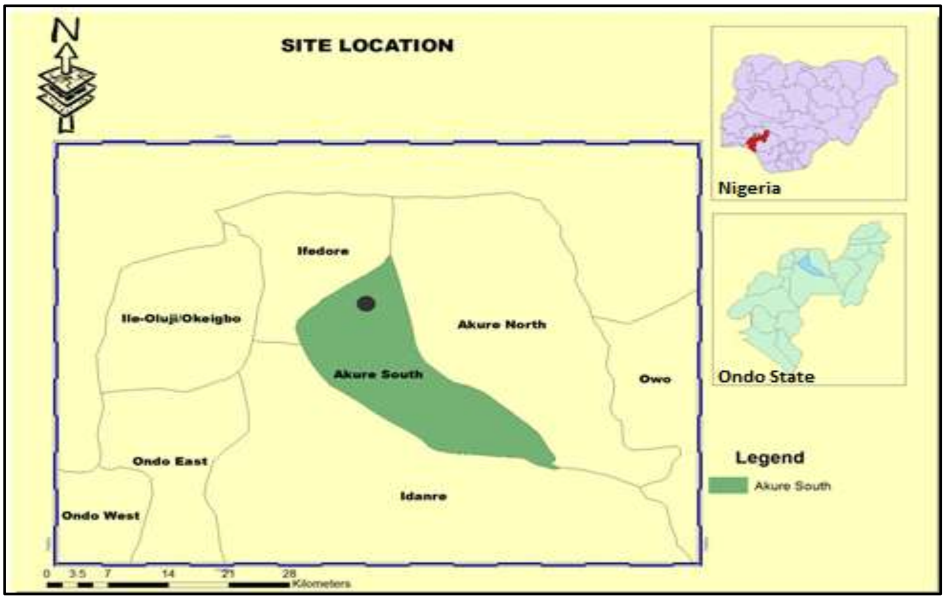

Figure 1: Map of the study location

COMPUTATION AND SIMULATION

With the aid of MATLAB photovoltaic project simulator depicted in Figure 2 and using relevant expressions as stated in equations (1) and (2); the real-time simulation of received solar power as well as the variability of the PV-system efficiency for a given period was determined. Also, a typical syntax for the variability of PV efficiency with four key parameters - cloud cover, solar intensity, relative humidity and heat buildup-were obtained online in real-time from Net-Logo archive. The peak performance of each PV system configuration was determined and the corresponding values of efficiency was used to evaluate the PV system performance on a diurnal and seasonal basis.The amount of electricity produced by a solar PV system is influenced by several factors, including solar irradiation (Si) at the site, ambient temperature, humidity, dust, cloud cover, the angle at which solar radiation strikes the panels, and the operational efficiencies of the system components [19].

[19],[20] proposed a model for estimating electricity generation potential of a PV system with defined module inclination and orientation. The model, given in equation (1), is based on the Photovoltaic Geographical Information System (PV-GIS) which accounts for the variables with the performance ratio, r_P (m^2/kWp), of the PV modules used in the system is defined as the ratio of the actual module efficiency, η, to the nominal module efficiency under Standard Test Conditions (STC), η_{nom} (kWp/m^2).

$$E = n_i r_p \, p_k S_i \quad (1)$$

where E (kWh) is the generated electricity for any given time interval; n_i is the number of

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days and P_k, installed peak power output (kWp). r_p is the performance ratio with constant value of 0.75 m^2/kWp [18], [19].
The effective energy output (E_{out}) obtainable from the solar installation for this location is estimated from equation (2):

$$E_{out} = H_r \times \eta_{sp} \times \eta_i \eta_b \eta_{cc} \times A \times N \quad (2)$$

where H_r is the received solar radiation at an instant of time, η_b, η_i and η_{cc} are analogous to performance ratio, and they represent battery, inverter and charge controller efficiencies respectively, η_{sp} is the solar panel efficiency, while A is the area of each panel, and N is the number of solar panels

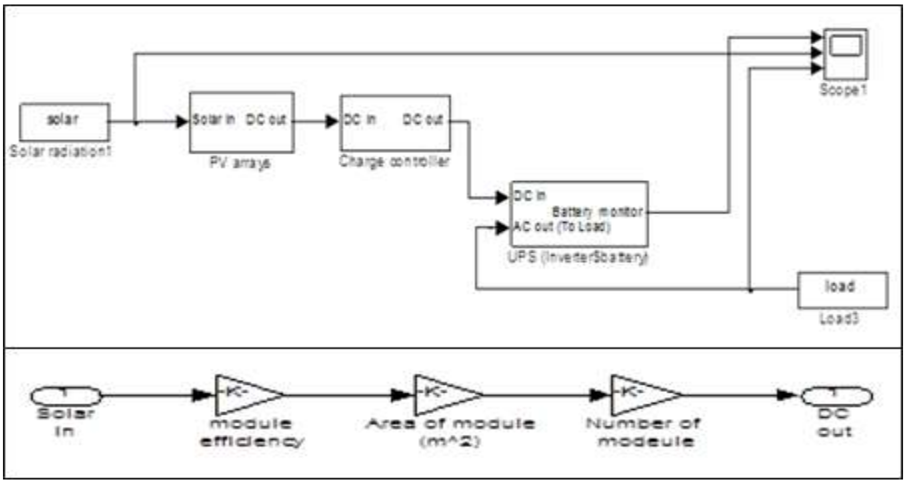

Figure 2: Syntax and schematic flowchart for the PV system simulation

III. RESULT AND DISCUSSION

VARIABILITY OF PV EFFICIENCY

Cloud cover significantly impacts the efficiency of a PV system. As cloud cover increases, power production efficiency decreases for all types of solar panel mounting systems. The tracking system is the most efficient, although it experiences a notable efficiency drop of approximately 9% as cloud cover increases from 1 to 100. The adjustable system has the highest decrease factor, around 10%, while the fixed solar panels have the least decrease factor, about 6%, as shown in Figure 3. Sun intensity positively influences PV system efficiency, though the effect varies across different mounting types. Using a scale from 5 to 30, with 5 representing the minimum sun intensity and 30 the maximum, at peak sun intensity, the tracking, adjustable, and fixed systems showed solar power production efficiencies of 23%, 20%, and 18%, respectively. When the sun intensity dropped to 20, both the tracking and adjustable mounts had 13% efficiency, while the fixed system had 11%. At the lowest sun intensity of 5, all three systems exhibited nearly the same efficiency, ranging from 2% to 3%, as shown in Figure 4. Relative humidity had the least effect on solar power production efficiency [21].

The tracking system's efficiency only decreased by about 2% as the relative humidity slider moved from 0 to 0.3, with no further decrease in efficiency as humidity increased. The adjustable mount's efficiency decreased steadily by 1%, while the fixed solar panels showed the lowest power output among the three mounting options, as shown in Figure 5. Without heat build-up, the fixed panels operated at 18% efficiency, the tracking system at 23%, and the adjustable system at 20%. However, with maximum heat build-up, the efficiency of the fixed system dropped by 5%, the tracking system by 9%, and the adjustable system by 7%, as shown in Figure 6. This goes further to show that while increased sun intensity is good for PV power production, increased heat build-up is detrimental.

Overall the tracking mount option is the most efficient PV system installation technique regardless of the inhibitive circumstance being confronted.

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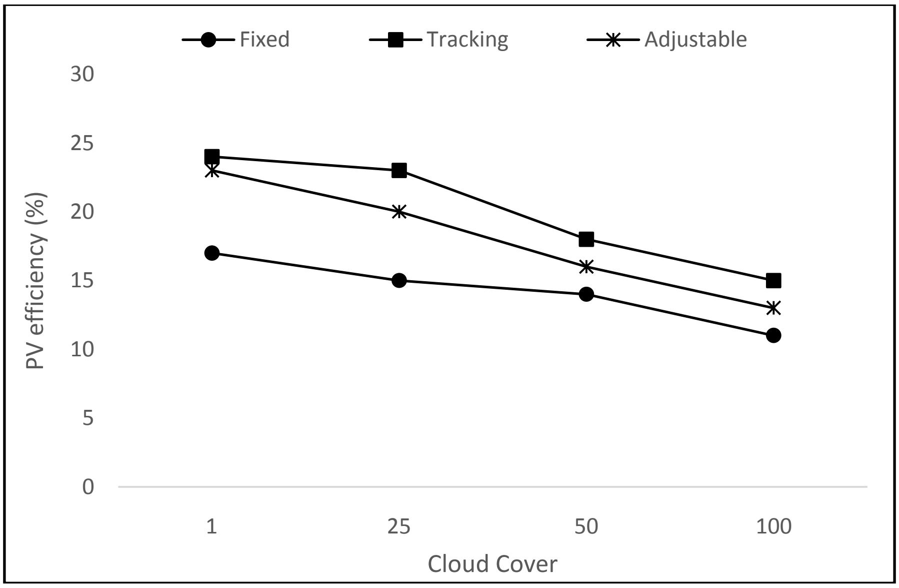

Figure 3: Variability of PV efficiency with cloud cover for different mounting options

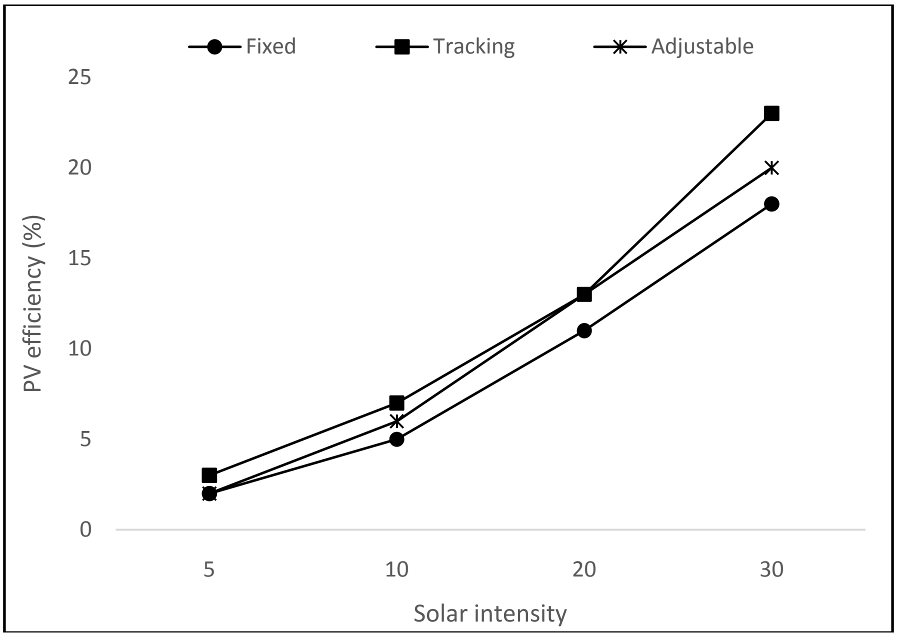

Figure 4: Variability of PV efficiency with solar intensity for different mounting options

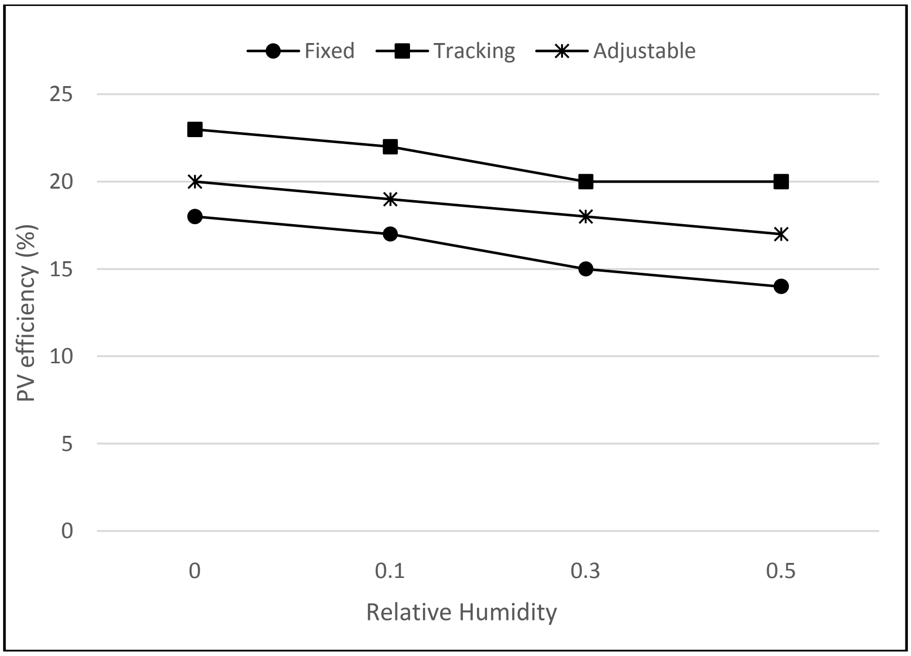

Figure 5: Variability of PV efficiency with relative humidity for different mounting options

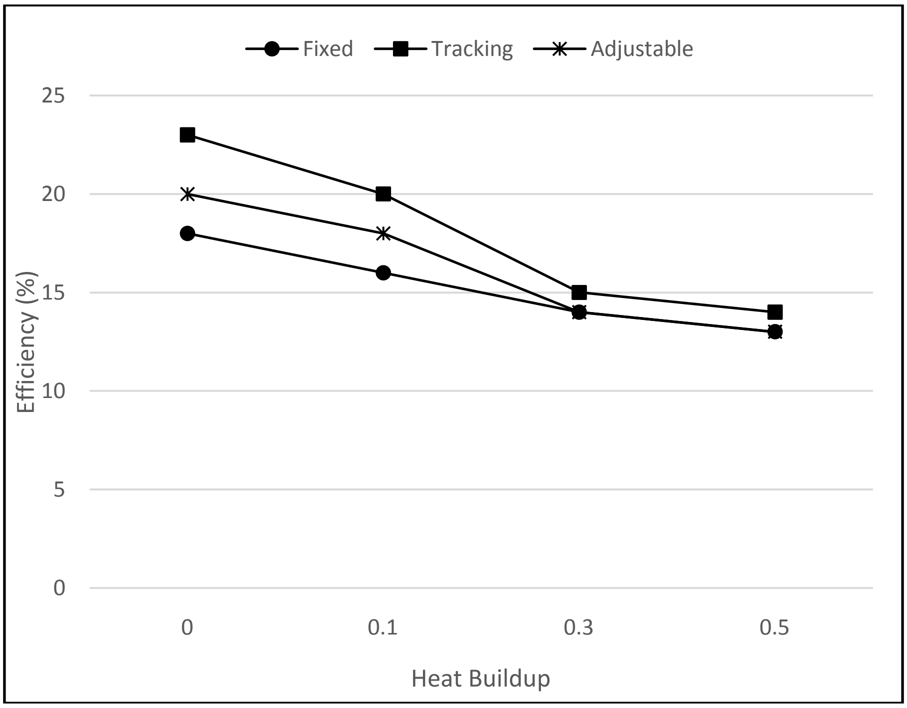

Figure 6:Variability of PV efficiency with heat buildup for different mounting options

DIURNAL AND SEASONAL VARIATION OF ESTIMATED SOLAR POWER

A typical 7-day diurnal profile of incident solar radiation at the study location for each of June and January 2018, representing rainy and dry seasons respectively is shown in Figure 7. The received solar radiation reveals that between midnight and 06:30 local time (LT), 0 W/m^2 was recorded; as well as between 18:30 and 23:30 in the 24-hour window. However, varying intensities of solar radiation were recorded between 07:00 and 18:30 LT, which peaks at 690.3 W/m^2) around 13:00 LT in response to the sunrise and sunset dynamics of the location.

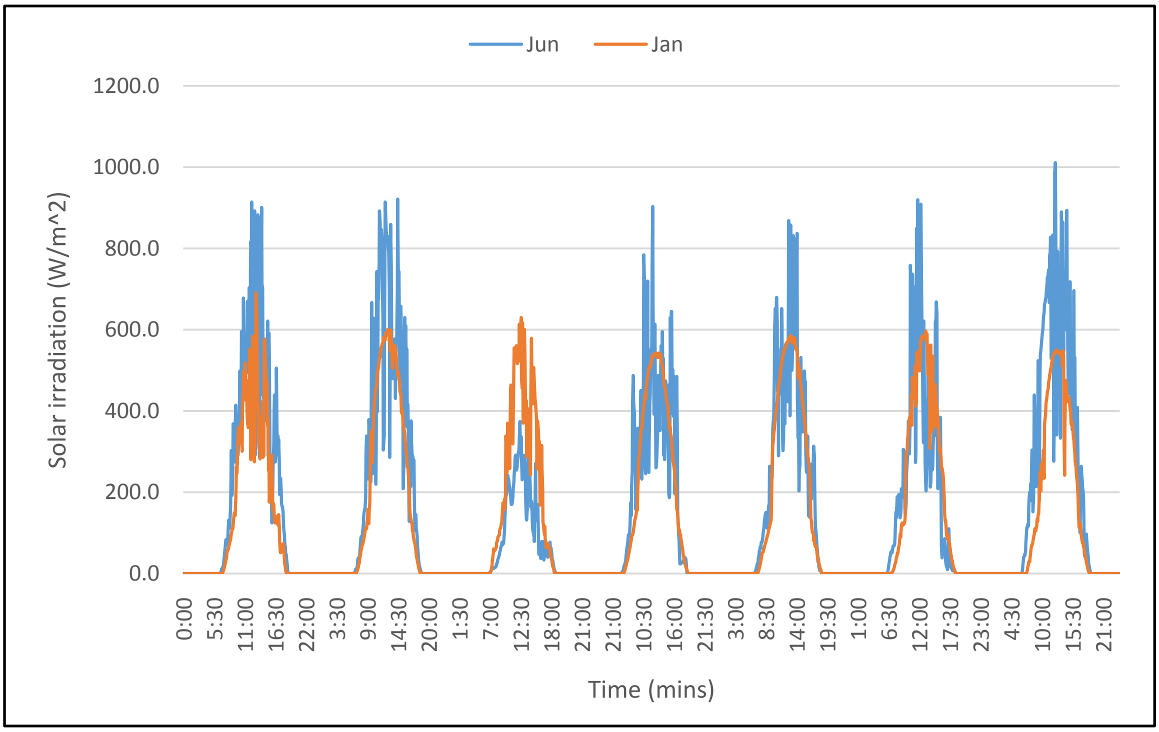

Figure 7: Diurnal profile of solar irradiation for rainy and dry seasons at the location

This trend of solar radiation distribution is typical of the tropical region and is often the pattern all year round; with slight variations experienced in the times of sunrise and sunset as well as in the intensities of the radiation, and its peak and off-peak periods. These high intensity radiations values were observed during both wet and dry season months. This is an indication that PV system installation is capable of providing energy all year round at a tropical location such as this; irrespective of the prevailing weather conditions. Although as expected, the peak values obtained during both seasons were of varying intensities, nevertheless, it is adequate to meet domestic energy needs as well as serving backup purposes.In order to evaluate the energy equivalence and comparative advantage of each PV mounting option, the peak performance values of each mounting efficiency were used to estimate the received energy of the PV system. Taking the fixed mounting option as reference, the difference in PV efficiencies between the adjustable and the fixed (A); and the tracking and the fixed (B); mounting options were evaluated on diurnal and seasonal bases.

The received irradiation values were then used to calculate the varying efficiencies of a PV system under different circumstances. At standard test condition of solar panel covering a hypothetical cross-sectional area of 20 m^2; the estimated solar energy balance for different mounting options are shown in Figures 8 and 9, for each of dry and wet seasons respectively. In general, tracking solar panels are the most efficient in generating the highest power output. However, they are also considered the costliest in terms of purchase, installation, maintenance, and repair.

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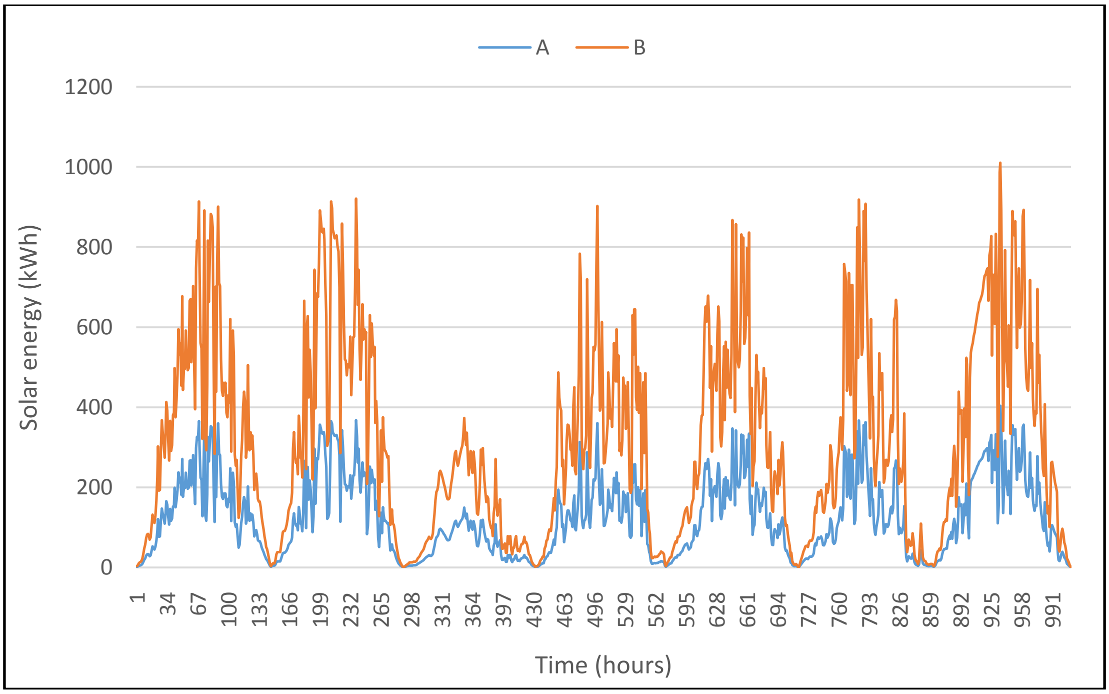

Figure 8: Diurnal profile of solar energy balance for typical rainy month

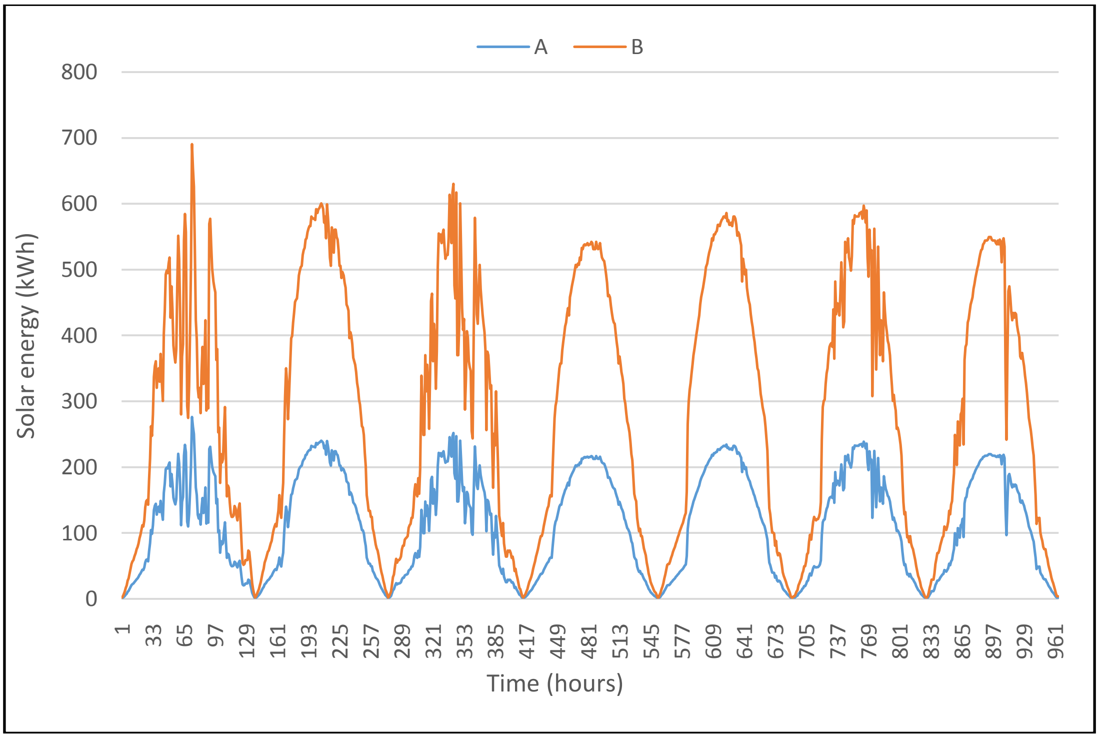

Figure 9:Diurnal profile of solar energy balance for typical dry month

However, the proportion of energy accumulated over a reasonable length of time can more than compensate for the initial incurred expenses. Table 1 shows the breakdown of energy balance for each of the prevailing weather variables and mounting option considered. The table highlights the accumulated solar energy balance achievable when each of tracking and adjustable mounting options are deployed for the PV systems. The gross value of incident radiation energy over one-week period for each of rainy season and dry season strongly suggests that the gains of using tracking mounting option for PV systems outweighs whatever initial hiccups it poses.

Table 1. Energy balance associated PV system efficiency (kWh)

Variable	Value	Jan (dry season)		Jun (wet season)	
		Tracking	Adjustable	Tracking	Adjustable
Cloud cover	1	38817700	33272314	44533740	38171777
	25	44363086	27726929	50895703	31809814
	50	22181543	11090771	25447852	12723926
	100	22181543	11090771	25447852	12723926
Sun intensity	5	5545386	0	6361963	0
	10	11090771	5545386	12723926	6361963
	20	11090771	11090771	12723926	12723926
	30	27726929	11090771	31809814	12723926
Relative humidity	0	27726929	11090771	31809814	12723926
	0.1	27726929	11090771	31809814	12723926
	0.3	27726929	16636157	31809814	19085889
	0.5	33272314	16636157	38171777	19085889
Heat buildup	0	27726929	11090771	31809814	12723926
	0.1	22181543	11090771	25447852	12723926
	0.3	5545386	0	6361963	0
	0.5	5545386	0	6361963	0

IV. CONCLUSION

This work has examined the variability of photovoltaic system efficiency for effective solar power production over Akure, southwest Nigeria. The comparative advantage of different mounting options - fixed, adjustable and trackingfor PV system installation was considered. The enhancement and inhibitive properties of selected weather parameterssuch ascloud cover, sun intensity, relative humidity and heat buildup were also examined. In all, tracking mounting option proved most effective as reported in literature. The diurnal profile of incident solar radiation measured using a standard weather station was used to estimate the real time energy capacity of PV system for this location. A hypothetical 20 m^2 solar panel at standard test condition (STC) yields electrical energy high enough to mitigate the energy problems of an ideal household. This dataset was also used in computing the energy balance due to variation in PV system efficiency brought by different mounting options and prevailing weather conditions. Best case scenario returns an efficiency range of 17-23% performance.

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